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The influence of chlorophyll-a and sea surface temperature on anchovy catch trends (2011-2024) in Kilwa, Tanzania

Renatus Shigi and Prosper L Mfilinge[ꚍ]

School of Aquatic Sciences and Fisheries Technology,
University of Dar es Salaam, P. O. Box 60091, Dar es Salaam, Tanzania

Keywords

Anchovy;
fisheries;
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Chlorophyll-a;
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Abstract

Anchovies exhibit varying trends in catch worldwide, with some regions experiencing declines in catch due to overfishing and environmental changes, while others remain stable or experience increases. Kilwa is among the most productive small pelagic fisheries along the Tanzanian coast. This study aimed to investigate the influence of Chlorophyll-a (Chl-a) and Sea Surface Temperature (SST) on anchovy catch trends in Kilwa. The study further examined the relationship between catch per unit effort (CPUE) and total anchovy catch, as well as its implications for fisheries management. The study was conducted at two sites: Kilwa Kivinje and Kilwa Masoko during both the northern eastern monsoon (high season) and the southern eastern monsoon (low season). The results revealed that catch at Kilwa Kivinje increased from 95,982 kg year^{-1} in 2011 to 123,754 kg year^{-1} in 2024. Whereas, at Kilwa Masoko, the catch increased from 63,988 kg year^{-1} in 2011 to 89,994 kg year^{-1} in 2024. Catches were consistently higher in Kilwa Kivinje than in Kilwa Masoko and peaked during the high season (Fisher's PLSD; $p < 0.0031$). The catch was composed of four species: *Encrasicholina devisi*, *Encrasicholina punctifer*, *Encrasicholina heteroloba*, and *Stolephorus commersonnii* which was the least dominant in the catches. Furthermore, results indicated that anchovy catches were positively linked to Chl-a levels [($R^2 = 0.763$, $t = 6.215$, $p < 0.0001$) Kilwa Masoko, ($R^2 = 0.597$, $t = 4.215$, $p < 0.012$) Kilwa Kivinje], but negatively to SST ($R^2 = 0.179$, $t = -1.618$, $p < 0.1316$) Kilwa Kivinje, ($R^2 = 0.349$, $t = -2.536$, $p < 0.0261$) Kilwa Masoko. Additionally, CPUE correlated positively with total catch, indicating that overfishing remains a concern, as increasing effort beyond sustainable limits can lead to stock depletion. These results highlight the need for effective fisheries management to optimize fishing effort while ensuring long-term sustainability in Kilwa.

Introduction

Small pelagic fish, particularly anchovies (Engraulidae), are vital in global fisheries, contributing significantly to food security and economic livelihoods (Hasini et al. 2020), despite the management problems (Kapapa et al. 2025). Anchovy fisheries account for nearly one-third of the world's total fish landings (Sekadende et al. 2020) and serve as a key ingredient in fishmeal production, while also being highly valued for their rich omega-3 fatty acids, which offer essential health benefits (Bodiguel and Breuil 2015). Beyond their nutritional and commercial

[ꚍ] Corresponding author: prospermfilinge@gmail.com
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importance, anchovy fisheries provide employment for thousands of fishers and traders, particularly in coastal communities (Sekadende et al. 2020).

In Tanzania, anchovy fishing plays a vital role in sustaining local economies and in trade, particularly in key fishing coastal regions such as Tanga, Mafia, Kilwa, Bagamoyo, Mtwara, and Dar es Salaam (Ibengwe et al. 2023, Kapapa et al. 2024). In Tanzania, both traditional fishing techniques, such as dugout and outrigger canoes, and modern methods like ring nets and purse seines are employed (Muhando and Rumisha 2008). However, despite their economic and ecological significance, anchovy stocks are increasingly vulnerable to a combination of environmental and human-induced pressures such as climate change (Kapapa et al. 2022). Furthermore, fishing efforts can have effects on the anchovy stocks. For example, high fishing effort can lead to overfishing, where the rate of fish being caught exceeds the rate at which they can reproduce and replenish their population, causing a significant decline in the anchovy population.

Changes in sea surface temperature (SST) and chlorophyll-a (Chl-a) concentrations, which influence primary production and fish distribution, are key factors affecting anchovy populations (Safruddin et al. 2018). Additionally, fluctuations in fishing effort, which include increasing fishing vessels, use of more powerful engines, and fishers, raise concerns about overexploitation (Dağtekin et al. 2022). Similar trends were observed in the Indian southwest coast, where mechanization and increased fishing efforts have led to significant depletion of marine species (Mohamed et al. 2010). While similar trends have been observed globally, with some regions such as Europe, North America, and Asia, with Africa experiencing significant losses of 9–49% of actual catches, severely impacting food security in low-income nations (Imran and Yamao 2014, Srinivasan et al. 2010), others have seen periodic increases in catches linked to favorable oceanographic conditions (Casaucao et al. 2021).

Despite the importance of anchovies in food security, employment, and income generation in Tanzania’s coastal fisheries. Few studies conducted in Tanzania coastal waters and anchovy fisheries have examined illegal fishing activities and habitat destruction, overfishing as contributors to declining stocks (Jiddawi and Ohman 2002, Silas et al. 2020), population dynamics (Fabiani et al. 2022), feeding habits and reproductive biology (Sululu et al. 2021). Due to declining stocks, some fishers have moved from nearshore to offshore fishing in the past decade, attributed to declining stocks from overfishing (Silas et al. 2020).

Little is known about the comprehensive research on the interplay between environmental factors and anchovy catch trends. Given the increasing demand for anchovies in both local and export markets, including destinations such as the Democratic Republic of Congo and Zambia (Komatsu and Kitanishi 2015), understanding these dynamics is critical for ensuring the sustainability of the anchovy fishery. This study aimed to investigate the influence of Chlorophyll-a (Chl-a) and Sea Surface Temperature (SST) on anchovy catch trends in Kilwa, Tanzania. In addition, it examined the relationship between catch per unit effort (CPUE) and total anchovy catch, highlighting implications for sustainable fisheries management, given the global fluctuation trend in achovy catch (Hinchcliffe et al. 2025).

Materials and Methods

Study area description

This study was conducted in Kilwa Masoko and Kilwa Kivinje, located in Kilwa District, Lindi, Tanzania. Kilwa Masoko, the administrative town of Kilwa District, is located on the tip of the Kilwa Peninsula, 8.9176° S, 39.5123° E. The area experiences a tropical coastal climate with warm temperatures throughout the year, moderated by sea breezes (daily averages ranging from about 25°C to 32°C) (TM Authority 2019). Kilwa Masoko is characterized by high humidity and two rainy seasons: a longer rainy period from March to May and a shorter one from October to December (TM

Authority 2019). Annual rainfall typically ranges between 800 and 1,200 mm, with a bimodal rainy season reflecting the long and short rains characteristic of the Tanzanian coast (TM Authority 2019).

Kilwa Masoko is a fishing and trading port where artisanal fisheries are a vital source of livelihood. As the district's main township, Kilwa Masoko has an estimated population of around 21,500 residents (Rugeiyamu et al. 2022) (based on recent census data). Fishing is a key livelihood here. While the entire district reportedly supports roughly 1,700 registered fishers operating about 600 vessels, Kilwa Masoko (with its mix of commercial and artisanal activities) is estimated to be home to approximately 250–300 active fishers. In this town, you might expect around 80–120 fishing boats actively servicing the anchovy fishery using a mix of traditional canoes and a modest fleet of small motorized vessels, reflecting the community's dependence on coastal fisheries. The township's infrastructure also supports modest market activities, and its proximity to heritage sites underscores its potential for integrated coastal resource management.

Figure 1: Map of Tanzania showing the location of Kilwa Masoko and Kilwa Kivinje.

Located just a few kilometers from Kilwa Masoko, Kilwa Kivinje (8°40′S, 39°15′E) is noted for its historical and cultural significance. Kivinje's coastal setting features sandy beaches interspersed with mangrove fringes, which play an important role in local fisheries and environmental protection. Like Kilwa Masoko, Kivinje experiences a tropical climate with warm temperatures throughout the year and seasonal rainfall patterns driven by the Indian Ocean monsoon, which support both artisanal fishing and small-scale agriculture.

Although not the district headquarters, Kilwa Kivinje is a vibrant fishing community with an estimated population in the range of 15,000–20,000 residents (figures based on local administrative records). Fishing is a central economic activity in Kilwa Kivinje, with local reports noting that dozens of dedicated fishers, operating a handful of traditional boats and a few modernized vessels, contribute significantly to the local anchovy fishery. Kilwa Kivinje is estimated to support roughly 350–400 active fishers. This community typically operates an estimated 150–160 small-scale boats dedicated to anchovy and other artisanal fisheries. The area's natural beauty, historical legacy, and evolving fisheries practices make it an ideal location to study the interrelations between environmental change and socio-economic resilience.

Sampling procedure

This study analysed catch data between seasons (south-eastern monsoon, and north-eastern monsoon), sites (Kilwa Kivinje and Kilwa Masoko), CPUE, the overall trend in the catches of anchovies from 2011 to 2024, and environmental factors, chl-a, and SST influencing the anchovy catches. To ensure comprehensive data collection and a clear understanding of the factors influencing the anchovy fishery, the study was conducted during both the high and low fishing seasons, corresponding to the north-eastern monsoon and the south-eastern monsoon, respectively. The high season, associated with the north-eastern monsoon, spans from November to March. During this period, the warmer waters typically result in higher fishing activity. Therefore, sampling was carried out from November 2024 to January 2025 to capture the peak fishing season, and the environmental conditions (chl-a and SST), including wind speed (as an extraneous variable), that may contribute to the fishery dynamics. Conversely, the low season, which coincides with the southern-eastern monsoon, extends from April to October (Silas et al. 2023). Cooler waters and reduced fishing activity characterize this period. Sampling was conducted from June to September 2024 at the peak of the season. Collecting primary data during both the high and low fishing seasons provides a comprehensive understanding of how seasonal variations affect anchovy catch. A comparative analysis of data from Kilwa Masoko and Kivinje provides insights into site-specific factors influencing anchovy catch dynamics, thereby informing management strategies aimed at regulating fishing effort, conserving anchovy stocks, and sustaining the livelihoods of local fishing communities.

Anchovy catches

Anchovy catches were obtained using ring nets (mesh size 8–10 mm) operated by artisanal fishers in inshore waters. Fishing typically begins around 20:00 hours, with vessels returning between 06:00 and 08:00 hours the following morning. Most boats are equipped with 40-horsepower outboard engines. In Kilwa Kivinje, approximately 99 vessels target anchovies daily (42 from Magengeni landing site and 57 from Mgongeni), whereas in Kilwa Masoko, 45 vessels participate (25 from Masoko Pwani and 20 from Jimbiza). The fishery at both sites illustrates a marked socio-economic disparity: low-income fishers carry out the labor-intensive harvesting, while ownership of vessels and infrastructure is concentrated among wealthier individuals. This arrangement creates a dependency dynamic, limiting the majority of fishers' control over production and restricting their share of economic returns.

Beach Management Units (BMUs) and fisheries officers assisted in the collection of data. Sampling was conducted monthly (during full moon/half, or last quarter). Catch data was recorded from all the sampling days (14-20 days per month), especially when lunar illumination was less than 70%. Ten boats were randomly selected at Kilwa Kivinje and Kilwa Masoko landing sites during the south-eastern Monsoon and the northern eastern Monsoon seasons. Just after boats landed from sea, the catch was weighed using a weighing balance, and the weight was recorded under the supervision of the BMU leader and a Fisheries Officer. Measuring the weight of the catch before auction is a common practice in Kilwa. Thereafter, catch from 10 randomly selected boats was thoroughly mixed, and then random samples of 5-10 kg, depending on the size of the catch, were taken and sorted out into species.

Species identification, particularly of *Stolephorus commersonnii*, was carried out on-site using external morphological characteristics such as coloration, fins, body shape, and size. Three specimens of *Encrasicholina* spp. were transported to the School of Aquatic Sciences and Technology, University of Dar es Salaam (Kunduchi campus), for further taxonomic confirmation. Species were identified to the lowest taxonomic level possible following the procedures outlined by Bianchi (1985) and Smith (2003). Anchovies were harvested using ring nets, which capture them efficiently while minimizing bycatch. For each fishing operation, metadata such as date, time, location, gear type, species identified, and environmental variables (e.g., wind speed and moon phase) were documented, as these factors influence fish schooling behavior during night fishing. Spatial data and specimen photographs were also collected for reference and validation. Furthermore, secondary catch data from 2011 to 2023 were obtained from the Kilwa District Fisheries Office.

Fishing effort and its effect on the anchovy fishery

Daily catch per unit effort (CPUE) was calculated as the total catch per day divided by the product of the number of fishers and the number of boats operating that day.

$$\text{Effort} = \text{Number of Fishers} \times \text{Number of Boats}$$

Annual CPUE was derived by dividing the total annual catch by the product of the number of vessels and the total fishing hours in that year.

$$\text{CPUE (daily)} = \frac{\text{Total Catch (kg or tons) in a Day}}{\text{Fishing Effort (units)}}$$

$$\text{CPUE (annual)} = \frac{\text{Total Catch in a Year (kg or tons)}}{\text{Total Fishing Effort in that Year}}$$

$$\text{Effort} = \text{Number of Vessels} \times \text{Average Fishing Days per Vessel}$$

$$\text{CPUE} = \frac{\text{Annual Catch}}{\text{Number of Vessels} \times \text{Fishing Hours per Vessel}}$$

These calculations were undertaken to assess the extent to which fishing effort influenced anchovy stocks. Elevated fishing effort can result in overexploitation, where harvest rates exceed the species' reproductive capacity, ultimately leading to stock decline. Information on the number of vessels, gear type and quantity, and the duration and frequency of fishing trips was obtained from BMU officers and through direct interviews with fishers.

Chlorophyll-a and Sea Surface Temperature

Chl-a and SST for 2011–2024 were obtained from the EU Copernicus Marine Service (https://marine.copernicus.eu). Spondylidis et al. (2023) noted that high-resolution ocean color remote sensing supports fishery planning by tracking fish distribution and productivity changes over time. These long-term satellite datasets provide a consistent record of surface ocean conditions that are closely linked to the productivity and distribution of small pelagic fish like anchovies. According to Semedi and Hadiyanto (2013), MODIS satellite data were used to predict fishing grounds for small pelagic fish, revealing a strong link between these areas and the distribution of SST and Chl-a concentrations. Chl-a levels indicate phytoplankton biomass (García–Nieto et al. 2024), which forms the foundation of the marine food web and directly influences the amount of food available for zooplankton, the primary prey of anchovies. When Chl-a levels are high, it usually indicates increased primary production, leading to better feeding conditions and often higher anchovy abundance and catch rates. Conversely, low Chl-a levels generally mean less prey availability, which can lead to decreased anchovy presence in coastal fishing areas.

SST plays an equally important role in shaping anchovy habitats and catchability. Anchovies are highly sensitive to thermal conditions, which affect not only their physiology but also the distribution of planktonic prey. Warmer surface waters, especially during the northeast monsoon season, promote vertical mixing and increase nutrient availability, supporting phytoplankton growth (Prasad et al. 2025). However, excessively high SST can cause stratification of the water column, limiting nutrient upwelling and potentially decreasing primary productivity (Lozier et al. 2011). Anchovies in Tanzanian nearshore waters typically occur where SST exceeds 28°C, generally from December to May (Manyilizu 2009), conditions that balance productivity and suitable thermal habitat. These thermal regimes also affect the aggregation behavior of anchovies, leading them to concentrate in predictable areas where catches are maximized.

By aligning anchovy catch data with seasonal and interannual fluctuations in Chl-a and SST, this study reveals how the interaction between ocean productivity and temperature patterns influences the temporal and spatial dynamics of anchovy fisheries in Kilwa Kivinje and Kilwa Masoko. Areas with Chl-a concentrations of 0.16–1.27 mg m^{-3} and SST within the optimal range are identified as potential fishing zones (PFZs), where anchovy schools are most likely to form and contribute to higher fishery yields.

Data analysis

Two-way analysis of variance (ANOVA) was used to test the effect of site and season on anchovy catches. Site (2 levels; Kilwa Masoko and Kilwa Kivinje) and season (2 levels; high fishing season (northern east monsoon season) and low fishing season (southern monsoon season) were entered as fixed effects factors to compare the amount of anchovy catches between sites Kilwa Masoko and Kilwa Kivinje, and between the high and low fishing seasons. Any significant site or season effects were further examined using Fisher's protected least significant difference (PLSD). A simple linear regression model was used to determine the relationship between anchovy catch and fishing effort, and between Chl-a and SST. A Bivariate scattergram with a supersmoother was used to illustrate trends in catches of anchovies recorded from 2011 to 2024 in Kilwa Masoko and Kilwa Kivinje. All statistical analyses were performed using SPSS. Statistical significance was determined when $p \leq 0.05$, and data were not transformed.

Results

Comparison of anchovy catches between sites and seasons

Four anchovy species were recorded: *Encrasicholina heteroloba* (Rüppell 1837), *Encrasicholina devisi* (Whitley 1940), *Encrasicholina punctifer* (Fowler 1938), and *Stolephorus commersonnii* (Lacepède 1803). The three *Encrasicholina* spp. dominated in the catch in both Kilwa Kivinje and Kilwa Masoko. The mean daily total catch differed significantly between sites (ANOVA; $F = 10.976$, $p < 0.0016$), with Kilwa Kivinje having a significantly higher mean daily total catch of 2649.543 kg day^{-1}, than Kilwa Masoko with a mean daily catch of 1376.310 kg day^{-1} (Fisher's PLSD; $p < 0.0041$). The mean daily catch also differed between the seasons (ANOVA; $F = 9.689$, $p < 0.0028$), with northern east monsoon season (referred to high season), having higher mean daily catches (overall for both sites) of 2839.444 kg day^{-1} than the southern monsoon season (referred to be low season 1513.027 kg day^{-1}

(Fisher's PLSD; $p < 0.0031$). During high season, Kilwa Kivinje alone had mean daily catches of 3821.786 kg day^{-1}, while Kilwa Masoko had 1781.538 kg day^{-1} ($t = 2.222$, df 25, $p < 0.0356$). However, catches were lower during the low season at Kilwa Kivinje (1868.048 kg day^{-1}), whereas at Kilwa Masoko (1047.063 kg day^{-1}) ($t = 2.628$, df 35, $p < 0.0127$) (Figure 2). Kilwa Kivinje had significantly higher catches than Kilwa Masoko, it was further observed that Kilwa Kivinje had a greater number of fishing boats engaged in anchovy fisheries (99) than in Kilwa Masoko (45).

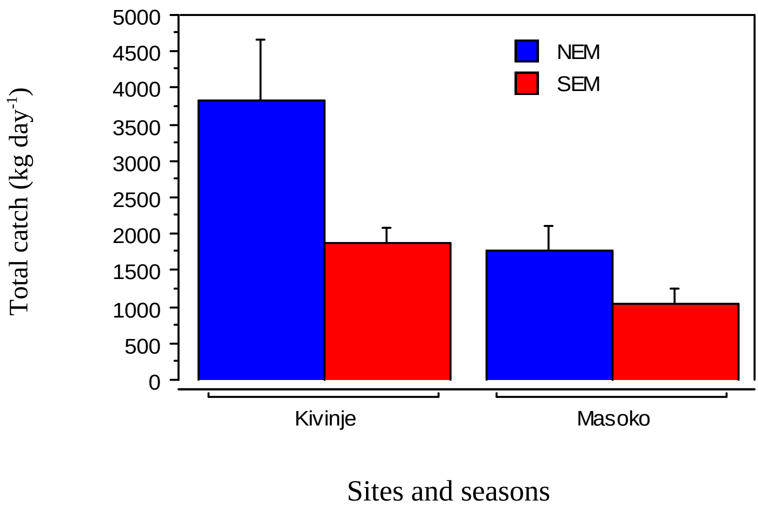

Figure 2: Comparison of anchovy total mean daily catch between sites (Kivinje = Kilwa Kivinje and Masoko = Kilwa Masoko), seasons (NEM = northern east monsoon, SEM = southern east monsoon) in Kilwa District.

The ANOVA results showed no significant interaction effect between site and season ($F = 1.993$, $p = 0.1632$), meaning that the influence of season on anchovy catches was consistent across sites, and vice versa. Thus, the observed variations are primarily explained by the independent effects of site and season .

Influence of catch per unit effort on anchovy catch

Anchovy catches increased proportionally with increasing CPUE across both sites and seasons, demonstrating a strong positive relationship between fishing effort and catch. At Kilwa Kivinje, daily anchovy catch showed a highly significant correlation with CPUE during both the SEM ($R^2 = 0.991$, $p < 0.0001$) and the NEM ($R^2 = 0.998$, $p < 0.0001$). Similarly, at Kilwa Masoko, the relationship was even stronger, with perfect or near-perfect correlations observed during the NEM ($R^2 = 1.00$, $p < 0.0001$) and the SEM ($R^2 = 0.998$, $p < 0.0001$) (Figure 3). These results suggest that CPUE is a reliable indicator of anchovy availability and fishing success in the study area, and that variations in catch between the sites are largely explained by changes in effort rather than random fluctuations.

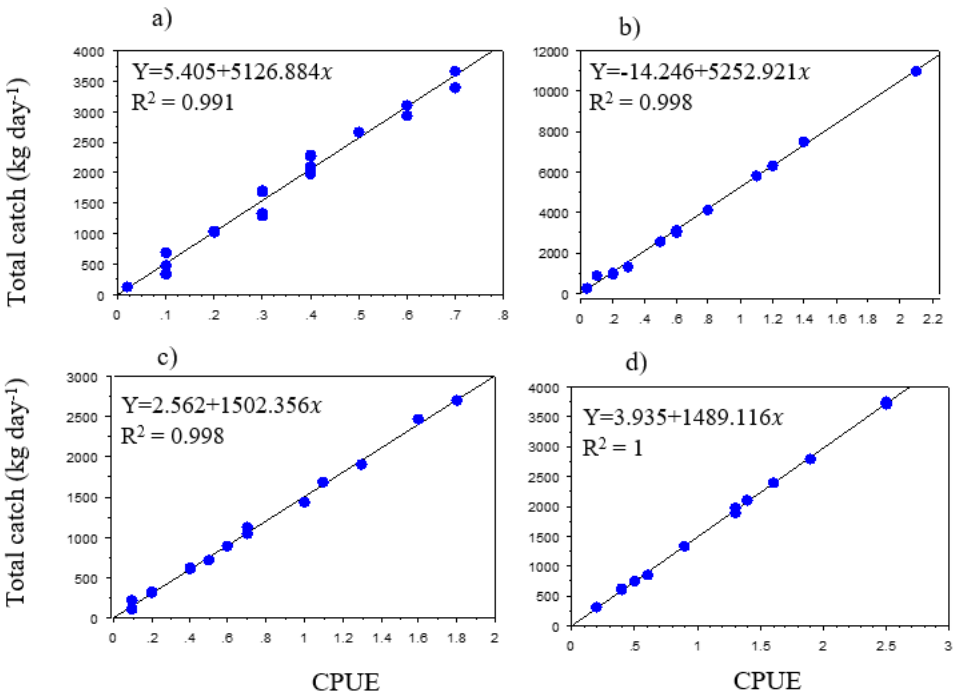

Figure 3: Relationship between catch and catch per unit effort (CPUE). a) Kilwa Kivinje during the southern east monsoon season, and b) during the northern east monsoon season. c) Kilwa Masoko during the southern east monsoon season, and d) during the northern east monsoon seasons.

Trends in anchovy catches

Results showed that total anchovy catch in Kilwa increased from 159,970 kg year^{-1} in 2011 to 213,748 kg year^{-1} in 2024, contrary to the study's assumption of declining catches. At Kilwa Kivinje, catches rose from 95,982 kg year^{-1} in 2011 to 123,754 kg year^{-1} in 2024, while at Kilwa Masoko they increased from 63,988 kg year^{-1} to 89,994 kg year^{-1} over the same period (Figure 4). Throughout the study period, catches from Kilwa Kivinje consistently exceeded those from Kilwa Masoko, likely reflecting higher fishing effort (in terms of high number fishing boats), more favorable landing infrastructure that support larger anchovy catches.

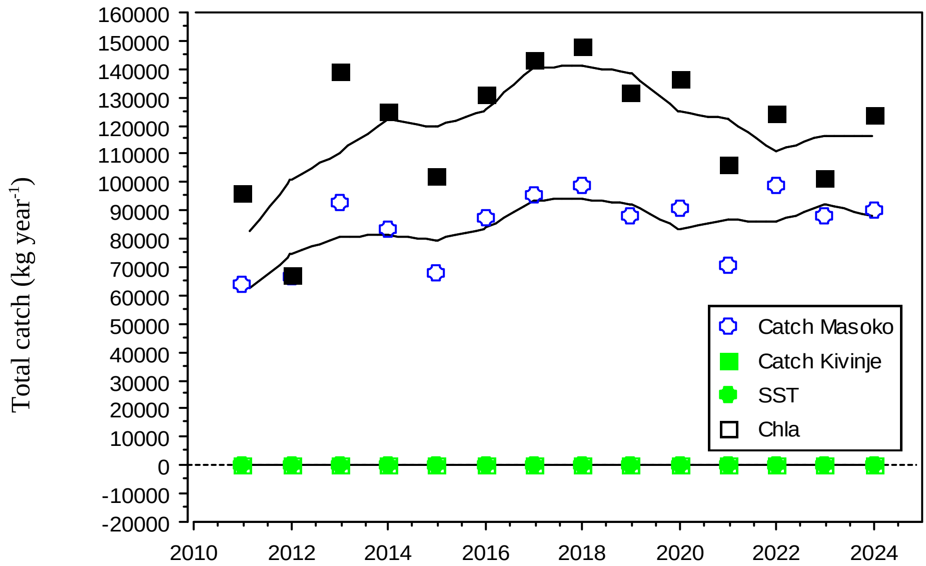

Figure 4: Bivariate scattergram with supersmoother showing trend in catches of anchovies recorded from 2011 to 2024 in Kilwa Masoko and Kilwa Kivinje, Kilwa District.

Influence of chlorophyll-a and sea surface temperature on anchovy catch

Results indicated that anchovy catches at both Kilwa Kivinje and Kilwa Masoko were significantly influenced by oceanographic conditions, showing a positive correlation with Chl-a concentrations and a negative correlation with SST. At Kilwa Kivinje, catch was significantly and positively correlated with Chl-a ($R^2 = 0.597$, $t = 4.215$, $p < 0.012$), suggesting that periods of higher primary productivity, as reflected by elevated phytoplankton biomass, enhance food availability at the base of the anchovy food web and support higher catches. Conversely, catch at this site was negatively correlated with SST ($R^2 = 0.179$, $t = –1.618$, $p = 0.1316$), although the relationship was not statistically significant, indicating that elevated temperatures may reduce anchovy abundance or availability.

At Kilwa Masoko, the relationship between Chl-a and catch was even stronger, with a highly significant positive correlation ($R^2 = 0.763$, $t = 6.215$, $p < 0.0001$). This suggests that phytoplankton productivity is a major driver of anchovy distribution and catchability in this area, likely due to the tight coupling between plankton dynamics and small pelagic fish populations. In contrast, SST exhibited a significant negative correlation with catch ($R^2 = 0.349$, $t = –2.536$, $p < 0.0261$), indicating that warmer conditions may alter water column stratification, reduce nutrient upwelling, and thus indirectly lower prey availability, ultimately leading to reduced anchovy catches (Figure 5). Overall, these results demonstrate that anchovy catches in Kilwa are primarily driven by bottom-up ecological processes, where Chl-a serves as a proxy for primary productivity and food supply, while SST exerts a moderating influence by shaping habitat suitability and prey distribution.

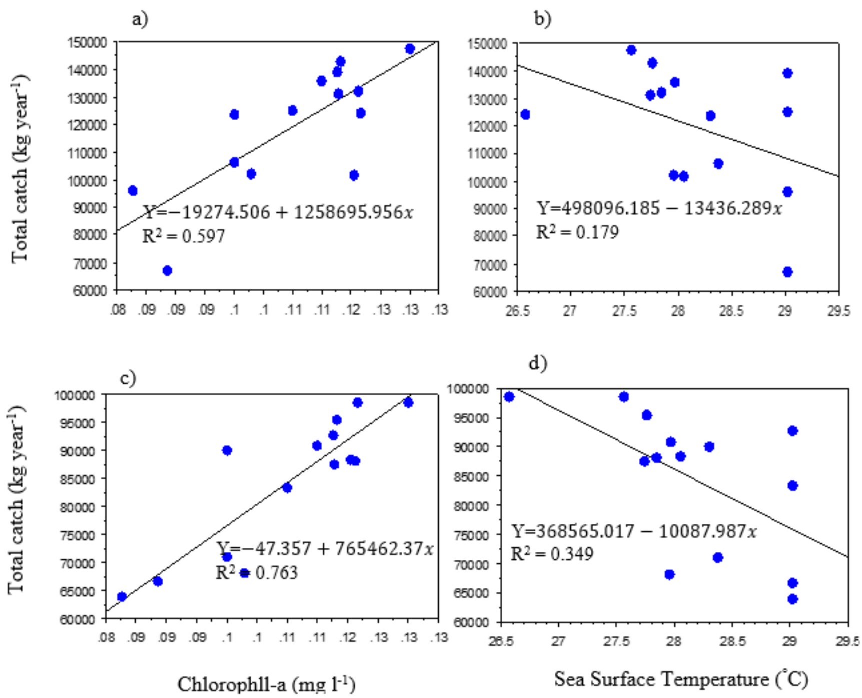

Figure 5: Relationship between catch, chlorophll-a (Chl-a), and sea surface temperature (SST). a) Total catch with chlorophyll-a at Kilwa Kivinje, and b) Total catch with sea surface temperature at Kilwa Kivinje. c) Total catch with chlorophyll-a at Kilwa Masoko, and d) Total catch with SST at Kilwa Masoko, Kilwa District 2025.

Discussion

Comparison of anchovy catches between sites and seasons

This study investigated the influence of Chl-a and SST on anchovy catch trends and examined the relationship between CPUE and total anchovy catch in Kilwa Kivinje and Kilwa Masoko during the northern east monsoon (high season) and the southern east monsoon (low season). Four Engraulid species *E. devisi*, *E. punctifer*, *E. heteroloba*, and *S. commersonnii* were recorded, with *S. commersonnii* least dominant. Similar dominance of *E. heteroloba* and *E. punctifer* in Kilwa Kivinje was reported by Sekandende et al. (2020) and Fabiani et al. (2022), consistent with fishers' accounts that both sites share common fishing grounds. *E. devisi* is more abundant in coastal upwelling regions due to its high reproductive capacity and adaptability to fluctuating environmental conditions (Checkley et al. 2017). The specific habitat preferences, fecundity rate, and distribution patterns of these species limit availability to coastal fisheries. *E. devisi* is year-round spawner found in shallow and subtidal waters throughout the life cycle (Dalzell and Lewis 1989), and reaches sexual maturity within three months.

The low abundance of *S. commersonnii* likely reflects its habitat preference and growth traits. Hoedt (1994) noted that *S. commersonnii* inhabits offshore waters and is captured only occasionally, suggesting solitary behavior. It also matures later than other anchovy species and spawns seasonally during warmer months, mainly September–January (Andamari et al. 2002, Sululu et al. 2021, Fabiani et al. 2022). Spawning coincides with the long rainy season and minor peaks in the short rains, when zooplankton and crustaceans are abundant, supporting gonad development (Parveen et al. 2022, Sululu et al. 2022).

Spatially, Kilwa Kivinje yielded higher catches than Kilwa Masoko. The absence of site–season interaction effects in ANOVA indicates that variation stemmed mainly from within-site and within-season factors. The higher catches at Kilwa Kivinje likely reflect greater fishing intensity, as 99 boats operate there compared to 45 in Kilwa Masoko. Fishing intensity and favorable oceanographic conditions are known to enhance anchovy aggregation (Bakun 2012). Seasonal variation was also clear: catches were higher during the northern east monsoon, when SST (29.5–30.5°C) and Chl-a (0.5–1.0 mg m^{-3}) support high primary productivity (Pauly and Zeller 2016, Safruddin et al. 2018). These warmer, nutrient-rich waters provide optimal anchovy habitat during this season.

Relationship between catch per unit effort and anchovy catch

These spatial and seasonal patterns are reinforced by the relationship between effort and catch. Anchovy catch correlated strongly with CPUE, emphasizing the role of fishing pressure. Similar effort-responsiveness has been documented in other small pelagic fisheries (Fréon et al. 2005). The near linear relationships (R^2 values close to 1.0) indicate that greater effort consistently produced higher catches, a hallmark of effort-dependent fisheries (FAO 2022). However, this also raises concerns: excessive effort risks stock depletion, even when catches initially rise (Hilborn et al. 2020). Historically, fisheries worldwide have suffered profit declines of 65–100% alongside rising operating costs, largely driven by fuel price increases and escalating effort (Ba et al. 2017). Concentrated fishing hotspots often show steep CPUE declines, signaling reduced abundance (Ramirez et al. 2022). The results stress the need for effective fisheries management to optimize fishing effort while ensuring long-term sustainability.

Trends in anchovy catches

Beyond effort, long-term catch patterns reflect environmental and technological drivers. Anchovy catches fluctuate globally with climate variability (Hinchliffe et al. 2025), yet in Kilwa they increased steadily from 2011 to 2024, contrary to the initial assumption of a declining trend. Gains at both sites (Kilwa Kivinje and Kilwa Masoko) may reflect improved technology, expanded fishing grounds, or favorable environmental conditions (Gutiérrez et al. 2012). Apart from the use of common fishing grounds, Kilwa Kivinje's consistently higher landings might point to local ecological advantages that boost productivity. These findings contrast with global reports of small pelagic declines under overfishing and climate stress (Pikitch et al. 2014). Nonetheless, rising catches should be viewed cautiously: positive trends do not guarantee sustainability, and that sustainability depends on ongoing monitoring of stock status and recruitment.

Moreover, higher landings do not always signal stock recovery. Increases may result from intensified effort, new markets, or exploitation of previously untapped areas. Without adequate recruitment, catch growth can mask population decline. Thus, while Kilwa's trends appear positive, they reinforce the need for fishery-independent assessments and ecosystem-based management that integrate both environmental variability and fishing pressure.

Influence of Chlorophyll a and sea surface temperature

Environmental drivers further clarify these dynamics. The positive correlation between anchovy catch and Chl-a highlights the central role of primary productivity. Elevated Chl-a indicates high phytoplankton biomass, forming the food-web base that sustains anchovy stocks (Majumder et al. 2021). The stronger relationship at Kilwa Masoko (R^2 = 0.763) compared to Kilwa Kivinje (R^2 = 0.597) suggests local differences in nutrient enrichment, possibly from upwelling or riverine inputs (Ware and Thomson 2005).

Conversely, the negative relationship with SST indicates that warming may constrain anchovy abundance, possibly through reducing chlorophyll-a levels, affecting small pelagic fish recruitment, reproduction and fish catches (Boyce et al. 2010, Semba et al. 2016), and altered metabolism, prey shifts, or impaired spawning (Peck et al. 2013). Kilwa

Masoko showed a stronger negative correlation ($R^2 = 0.349$) than Kilwa Kivinje ($R^2 = 0.179$), pointing to site-specific sensitivities. These results align with global studies showing small pelagic species are temperature-sensitive, with warming trends shifting distributions and reducing abundance in some regions (Cheung et al. 2010). Long-term, fishery-independent monitoring is essential to fully capture climate impacts on Kilwa's anchovy populations.

Limitations of the Study

Although this study provides important insights into the dynamics of Kilwa's anchovy fishery, its findings should be interpreted with some caution. The analysis relied heavily on artisanal catch records, which, while useful for long-term monitoring, are often affected by reporting gaps, inconsistent record keeping, and differences in fishing practices among fishers (Pauly and Zeller 2016). The focus on four dominant species *E. devisi*, *E. punctifer*, *E. heteroloba*, and *S. commersonnii* means that the role of other small pelagics, which also contribute to ecosystem health and fisheries productivity, remains underexplored. Environmental drivers were narrowed to SST and Chl-a, even though other factors such as salinity, dissolved oxygen, nutrient inputs, wind-driven circulation, and upwelling can strongly shape anchovy distribution (Bakun 1996; Barange et al. 2020). Satellite-derived data, while valuable, may overlook fine-scale changes in nearshore waters where most artisanal fishing occurs, and grouping results into broad monsoon seasons may have masked shorter-term oceanographic events (Checkley et al. 2017). Finally, because the study was observational rather than experimental, the correlations between catches, Chl-a, and SST cannot be taken as direct evidence of cause and effect. Other influences (extraneous variables) such as new fishing technologies, socio-economic pressures, or shifts in recruitment could also explain the patterns observed (Hilborn et al. 2020). Recognizing these limitations highlights the importance of adopting more integrated approaches in future research. This could include fishery-independent surveys, long-term monitoring, and the use of modern genetic tools such as DNA barcoding and eDNA metabarcoding. These methods would not only refine species identification but also provide deeper insights into genetic diversity as well as the structure of populations and communities.

Conclusion

This study reveals how both environmental variability and fishing effort shape anchovy catches in Kilwa, with notable differences between Kilwa Kivinje and Kilwa Masoko. The strong link between CPUE and catch underscores the need to regulate effort levels, while the rising catches from 2011–2024 suggest a measure of resilience in the fishery. At the same time, the positive link with Chl-a and the negative relationship with SST show how closely anchovy abundance is tied to shifts in ocean productivity and temperature. Together, these findings point to both opportunity and risk: Kilwa's anchovy fishery appears productive, but its long-term sustainability depends on continuous monitoring and effective management.

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